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PROJECT ADMINISTRATION DATA SHEET

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Project No. E-24-653 (E-24-353 c/s) DATE 4/5/82

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Sponsor: USDA, Forest Service; Southeastern Forest Experiment Station

Type Agreement: No. 18-926

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Cost Sharing: $2,499 GTRI/~~GIT~~

Title: System Dynamics Forest Sector Demonstration Model

ADMINISTRATIVE DATA

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Defense Priority Rating: None

Security Classification: None

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GEORGIA INSTITUTE OF TECHNOLOGY

OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION SHEET

Date 7/11/83

Project Title: System Dynamics Forest Sector Demonstration Model

Project No: E-24-653

Project Director: Dr. Willard Fey

Sponsor: USDA, Forest Service

Effective Termination Date: 6/11/83

Clearance of Accounting Charges: 6/11/83

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E-24-653

USE OF SYSTEM DYNAMICS APPROACHES TO REGIONAL FOREST SECTOR MODELS

by

Vernon L. Robinson and Willard R. Fey

The Forest and Rangeland Renewable Resources Planning Act of 1974 (RPA) and the National Forest Management Act of 1976 (NFMA) prescribe how land and resource management planning is to be conducted on National Forest System lands. One of the guiding principles underlying these acts is the recognition that the National Forests are ecosystems and their management for goods and services requires an awareness of the interrelationships among plants, animals, soil, water, air and other environmental factors within such ecosystems. Therefore, in the development and maintenance of land management plans, the planners are to use a systematic interdisciplinary approach to achieve integrated consideration of the physical, biological, economic and other services forthcoming from the National Forest System. Specifically, a team representing several disciplines is to be used at each level of planning to ensure coordinated planning which addresses outdoor recreation, range, timber, watershed, wildlife and fish, and wilderness opportunities. Clearly, an integrated ecosystem analysis and a human intervention and management analysis is essential to meet the requirements of these acts. The research described below is specifically designed to provide a vehicle for accomplishing such an analysis.

DEFINITION OF SYSTEM DYNAMICS

System Dynamics is a method of modeling the complex interactions that characterize our biological, engineering, managerial, organizational, and social systems. Its distinguishing feature is the application of feedback control principles to model problems. A feedback system exists whenever the environment leads to a decision that results in an action which affects the environment and thereby influences future decisions (6). Feedback control is fundamental to all life and human endeavor. For example, a thermostat receives temperature information and decides to start the furnace; this raises the temperature, and the furnace is shut off. A person senses that he may fall, corrects his balance, and thereby is able to stand erect. In both cases, a closing of the loop occurs and a delay intervenes between the initial action and the fed back results. Closed loops and time delays are characteristic of all feedback processes.

The loops do not function separately, but rather are coupled together to form complex feedback systems that are whole interacting entities. Change in one system part eventually has an impact everywhere in the system. The continuing operation through time of these loops creates the performance time patterns of the system's variables. The study of feedback systems deals with the way information is used

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for the purpose of control. It helps us to understand how the amount of corrective action and the time delays in interconnected components can lead to system behavior. Thus system dynamics is based on the philosophy that the behavior of a system is principally caused by the system's structure. The structure includes not only the physical aspects of the system but, more importantly, the "policies" that dominate decision making within the system.

A second aspect of the system dynamics philosophy is the concept that systems are viewed most effectively in terms of their underlying flows of people, money, materials, information, etc. A meaningful framework then results from tracing the cause-and-effect chains through the relevant flow paths of the system. A causal loop diagram is typically employed as the first step in modeling. These diagrams show the major cause-and-effect links between the system variables; indicating the direction of the linkage, and denoting the major feedback loops and their polarity. A positive feedback loop has very predictable behavior in response to a change induced in any of its variables. The loop can only act to reinforce or accelerate that initial change. A negative feedback loop on the other hand acts to counter the direction of initial change in any of its variables.

From a system dynamics perspective, all systems can be represented in terms of level and rate variables with auxiliary variables used to represent goals and other concepts that affect the rates. A level is an accumulation or an integration over time of flows or changes that come into and out of the level. For example, forest inventories grow or diminish over time depending upon the relative growth and harvest of the forest. A rate variable on the other hand is a flow or a decision that controls a flow into or from an accumulation that changes over time as a function of the influences acting upon it. Forest system relationships can be translated into level, rate and auxiliary equations that can be simulated by computer using a specially designed compiler program called DYNAMO (11).

ECOLOGICAL SYSTEMS AS FEEDBACK PROCESSES

Ecology is the study of organisms in relation to their environment (10). A community is an aggregation of living organisms having mutual relationships among themselves and their environment. Forest ecology, therefore, is concerned with the forest as a biological community with the interrelationships between the various trees and other organisms comprising the community and between these organisms and the physical environment in which they exist. The forest community and its habitat together comprise an ecological system, or ecosystem, in which the constituent organisms and their environments interact in a complex energy cycle.

All organisms within the ecosystem depend upon the utilization of an external source of energy, solar radiation. A portion of this energy is used by plants to manufacture food from inorganic substances by the process of photosynthesis (9). Although some of the resulting potential energy is released through respiration, most of it, in the early stages of growth, is transformed into organic substances which form the structure of the plant. Over time this biomass accumulates with the result that a greater amount of the food energy produced goes into the maintenance of the plant and less is available for the production of additional biomass. Typically, the biomass increases slowly at first, then more rapidly but it slows down gradually again as the plant matures. Thus, in a mature ecosystem, the energy fixed tends to be balanced by the energy lost through respiration. The growth of a great variety of populations--representing microorganisms, plants and animals--have been shown to follow this sigmoid pattern. For example, in Figure 1 the general pattern of a 100-day autotrophic succession in a microcosm (3) is compared with a 100-year forest succession (8). While the numerical magnitudes of the forest variables are considerably larger than those of the laboratory microcosm, there is a remarkable similarity in their modes of behavior over time.

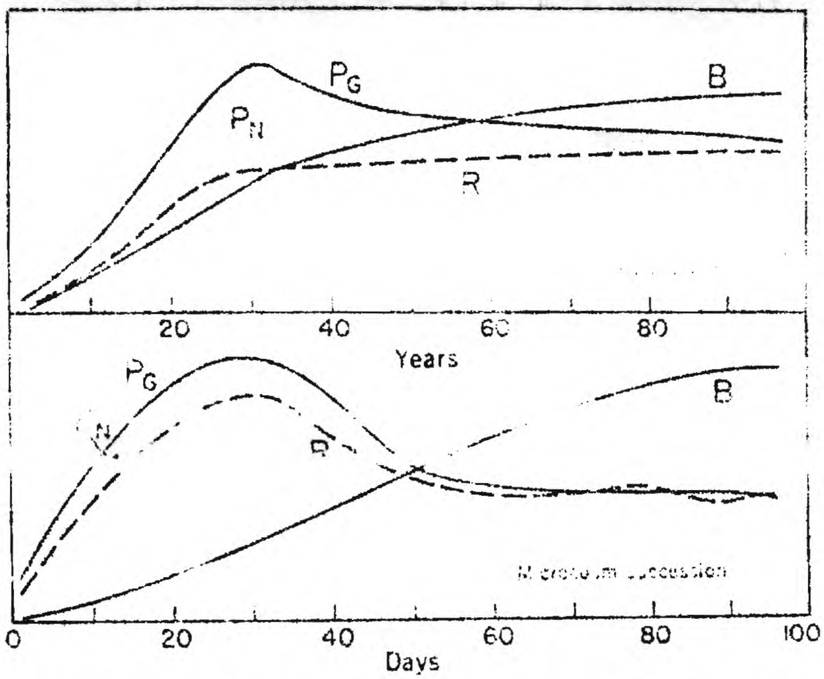

Figure 1. Comparison of Ecosystem Development in a Forest and a Laboratory Microcosm. P_g, Gross Production; P_n, Net Production; R, Total Community Respiration; B, Total Biomass

The accumulated biomass provides a source of potential energy for animals who as consumer organisms oxidize a considerable portion of the consumed material to release kinetic energy for their body maintenance and transform the remainder into body structure. Eventually, all organisms die and bacteria and fungi dissipate the potential energy of the organic debris, transforming it into inorganic elements. From this inorganic state the plants may again use the dissolved nutrients in photosynthesis to manufacture food, thus completing the energy cycle. This cycle is known to have negative polarity, returning the system to a state of trophic equilibrium after an exogenous perturbation (1, 2, 9).

The cycling of mineral nutrients from the soil to the vegetation and back again is basic to all life. Therefore, it provides a useful starting point for modeling the interrelationships that exist in a forest ecosystem. In such a system energy, primary production, biomass, dead organic matter, and inorganic nutrients are accumulated as described above. These accumulations are determined by the material flows around the energy cycle and by the time delays that exist between these fundamental ecological variables.

This real life phenomenon is captured in the dynamic hypothesis proposed by Gutierrez and Fey (7), Figure 2. The identified variables represent levels or flows. The links with arrows represent cause-and-effect relationships between variables with the variable at the tail of the link influencing the variable at the head of the link. A positive sign in the link means that the variable at the tail and the variable at the head of the arrow change in the same direction. If the tail increases, the head increases. If the tail decreases, the head decreases. On the other hand, a negative sign in the link means that the tail and head variables change in opposite directions.

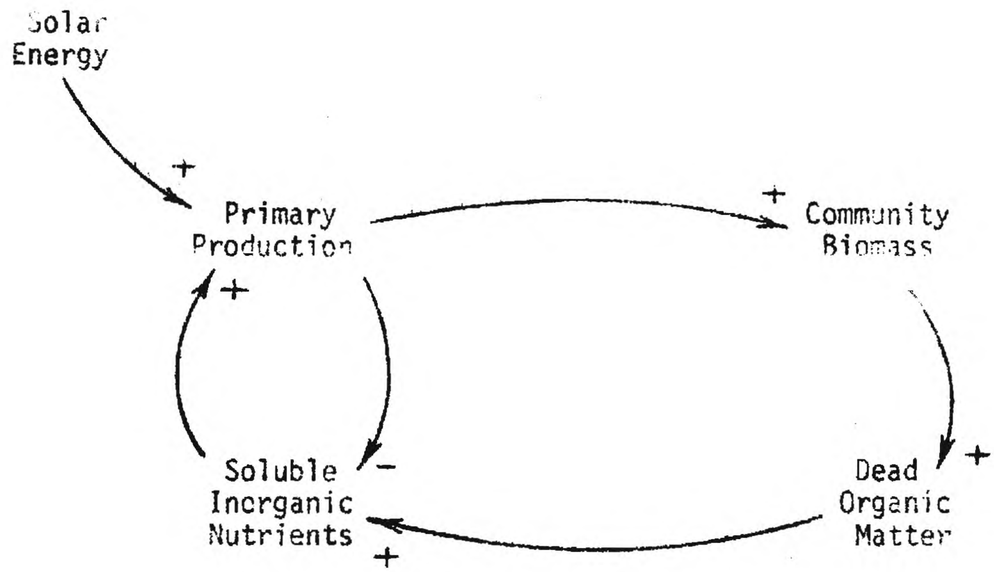

Figure 2. Dynamic Hypothesis of the Energy Cycle

Energy flows into the ecosystem and is either stored or gradually dissipated in the performance of work around the loop. The coupled feedback loops account for the circulation of matter around the energy cycle. An increase in either solar energy or inorganic nutrients increases primary production. But, an increase in primary production decreases the availability of inorganic nutrients. This loop possesses negative polarity as it has an odd number of negative linkages in the loop. One positive loop is the nutrient recycling loop. An increase in primary production increases the community biomass. An increase in biomass increases the amount of dead organic matter. Finally, the feedback linkage between the loops occurs when the organic debris is decomposed into inorganic nutrients.

Each arrow in the causal loop diagram denotes a time delay. The values of the delays around the loop are not limiting during the early stages of growth, and they are not limiting as long as the reservoir of soluable inorganic nutrients remains high in relation to the biomass. However, as the mature stages of plant life are approached, the functioning of the process increasingly depends upon the capacity of recycling of nutrients. Thus, the negative primary production/inorganic nutrient loop controls the state of trophic equilibrium within the model system just as it does in the real ecosystem.

The coupling of the positive and negative feedback loops will produce a time history of forest biomass accumulation which is consistent with that shown in

Figure 1. Obviously, the causal loop diagram is incomplete.[1] In order to construct a testable model, this hypothesis must be articulated in terms of quantifiable inter-loop and intraloop relationships representing other variables of interest that exist within the forest ecosystem. The purpose here is merely to demonstrate that the balance of nature means that ecological systems are feedback processes. Hence, system dynamics is an appropriate tool for studying the complex interrelationships that exist among the trees, shrubs, herbs, bacteria, fungi, protozoa, invertebrates, vertebrates, oxygen, carbon dioxide, water, minerals, and dead organic matter which in their totality constitute a forest. The modeling of human intervention upon these biological processes is the subject of the next section.

HUMAN INTERVENTIONS IN FOREST ECOSYSTEMS

There are many aspects of the natural forest ecosystem that are beneficial to individual humans and human society. Therefore, one aspect of human intervention in the forest is use of the environment, land and biological products of the forest. The forest environment provides recreation and wilderness experiences, the land contributes water and minerals, and the living forest produces timber, forage for domesticated animals and wildlife and fish for hunting and fishing.

Since there is so much of value in the forest, a natural desire arises to increase, if not optimize, the forests capacity to generate these benefits. A second type of intervention occurs when humans attempt to control the type and rate of growth of forest products. This can be done through such actions as seeding, fertilizing, selective cutting and prescribed burning. Construction is often initiated to facilitate growth, harvest or utilization. Roads, fences, water sources for grazing animals and recreation and mining facilities are examples of this kind of intervention.

The former kinds of intervention are undertaken intentionally by the owners or managers of the forest to protect, develop or use the forest's benefits. Another type of intervention involves unintentional impacts on the forest. Since there are so many people and so much mobility and industrial activity, even remote forest areas feel the impact of human action. Air, water and solid waste pollution are extensive. Acid rain is becoming a major problem. Unauthorized timber cutting, grazing, hunting and fishing are common. Intentional weather intervention (e.g., cloud seeding) for agricultural and other purposes often influences forest rainfall. Unintentional weather influences such as increasing carbon dioxide concentration in the atmosphere from fossil fuel use and ozone destruction in the upper atmosphere influence temperature, rain frequency and volume, and solar radiation availability, intensity, and wave length composition.

Despite the growing importance of these latter unintentional interventions, this paper focuses on the intentional interventions by forest managers. There are several characteristics of these impacts that are important. The first consideration is the balance required between protection or development and use. Too much use destroys the forests' ability to reproduce itself. Too little use provides

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1 A complete dynamic hypothesis of ecosystem succession can be found in Gutierrez and Fey (1980). While this hypotheses was developed to represent a grassland ecosystem, it has general applicability to the process of secondary succession.

inadequate benefits to the users. "Appropriate" use simultaneously provides significant benefits while enhancing forest productivity and vigor.

The second consideration is the synergy or conflict among the uses. Usually a utilization action such as cutting an area for timber has benefits and detriments relative to other uses. For example after cutting, an area frequently becomes available for grazing for a period of time after new trees are established and until they are large and dense enough to interfere with grazing. Temporary detriments arise as certain creatures' habitats are destroyed along with some of the scenic beauty of the area. These tradeoffs become important considerations in forest management decisions.

A third consideration is the response time horizon. An action may be beneficial in the short run for some purpose, but detrimental in the long run for that same purpose or others and vice versa. Mining an area may provide significant immediate revenues, but may contaminate the land in such a way that reforestation cannot take place for many years. Burning may destroy biomass in the short run, but increase plant productivity and habitats of desirable creatures in the long run.

The interventions by forest owners usually require continuing actions, observation and evaluation to ensure that the desired results occur and persist. This requires a continuing organization and management with authority and responsible to determine and carry out the required tasks. The United States Forest Service is an obvious example of a continuing organization engaged in forest management necessitated by the need to continuously balance use and protection, control coordination and tradeoffs between uses, and reasonably balance short and long range benefits and detriments.

Financial considerations and constraints arise as soon as a continuing management activity is supported. Furthermore, the balancing of protection and use, the control of multiple uses and the balance of short and long range considerations all contribute to the occasional need to provide costly intervention services and activities before benefits are realized. If money is required, a source must be found and control must be exercised over the utilization of funds. The consequence of this reality is that the forest biology, the decision structures of the associated human organizations, and the financial aspects of forest benefits and capital and operating costs of the organizations all become interrelated in the short and long run to form a single entity -- the forest management system. The biological, human and financial aspects of this system are related through coupled feedback loops that operate continuously through time to create the patterns of change of the system's variables. A simplified example of some of these interrelationships is illustrated in the causal loop diagram of Figure 3.

The natural forest ecosystem elements are shown at the top of the figure. These include the forest biomass, the production and mortality flows of the biomass and the nutrient pool that closes the cycle. Below are shown some of the timber use variables. These include timber product inventory, consumption, consumption desired, and price; and the human population and economic system vigor that originate the demand. Like the forest ecosystem variables, the timber product consumption variables influence each other through closed loop relationships. For example, an increase in desired timber product consumption will increase timber product consumption. This will decrease timber inventory which after a time delay

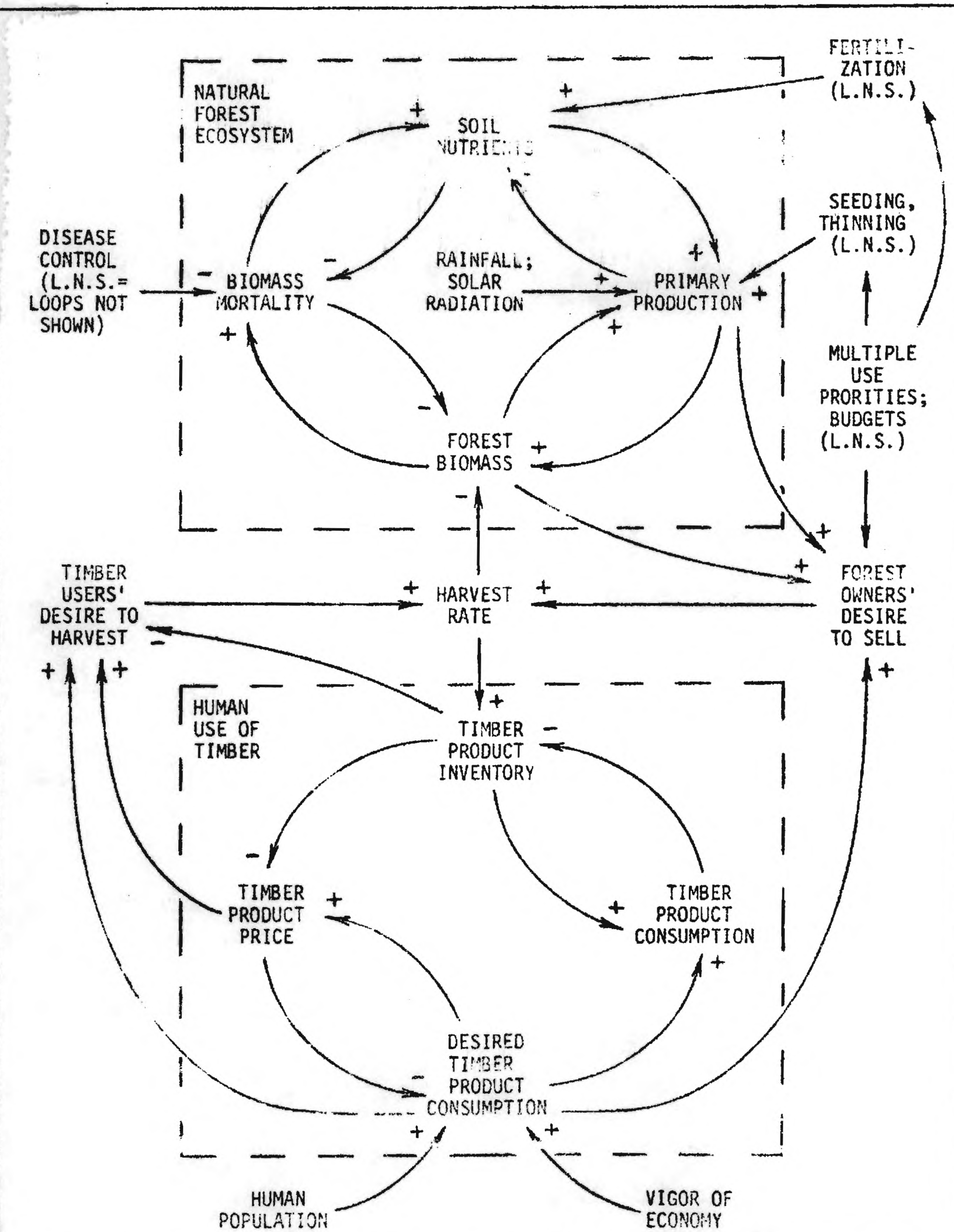

Figure 3. Partial Forest Management System Diagram Showing Ecological, Human and Financial Feedback Interactions

will stimulate an increase in timber product prices. Increased prices will reduce desired consumption and thereby close a negative loop of causal influences.

The human utilization system and the natural ecosystem are coupled through the forest harvest rate. This intervention is controlled by the relative harvesting desires of the forest owners and the timber users. The timber users' desire to harvest is influenced in part by the current availability of timber, timber product prices and expected timber product demand. Forest owners' desire to sell timber is partially influenced by the amount of standing timber (biomass), expected timber growth rates, and expected timber demand. Timber price, an important consideration in both party's desires, has been omitted to simplify the diagram. Obviously, it and other influencial variables would be included in a more complete representation.

The purpose of Figure 3 is not to completely describe the forest management system, but rather to illustrate the closed loop nature of the couplings between the natural ecosystem, human consumption (intervention) and financial considerations (as reflected here in the timber product price.) Other closed loop interventions occur when growth rate, nutrient pool and mortality rate are influenced by decisions to seed, fertilize and burn. These activities arise when a need for them is perceived and money is made available in budgets to carry them out. The perceived need is established by observations of the biomass, growth and mortality conditions in the forest and expected timber demand that are then related to the multiple use goals established by forest owners or the Congress. Budgets reflect the needs when legislators understand the needs and the consequences of not meeting them. The functioning of these feedback relationships through time creates the time histories of the variables. Increase or decline, oscillation or stagnation result from the way the loops are organized and coupled together. The System Dynamics methodology was created to quantitatively analyze such situations.

SYSTEM DYNAMICS ANALYSIS OF FOREST MANAGEMENT SYSTEMS

The System Dynamics Method provides for the analysis and synthesis of dynamic feedback systems of all types. This is accomplished by carrying out certain activities in a prescribed logical sequence (5). The sequence begins with the clarification of the system's objectives and time history performance. Then the functional operation of the system is carefully observed and measured. The understanding of performance and operation obtained from the preceding investigations serves as a basis for developing a written dynamic hypothesis which identifies the feedback loops that are perceived by the analyst to create the major performance characteristics. Quantitative modeling of the relationships that compose these loops is performed to provide a basis for testing the hypothesis. The resulting model (set of dynamic equations) when simulated under a variety of conditions can be used for many purposes. Proposed changes in the feedback structure of the model can be tested to determine their effect on system performance, which is often found to be counter-intuitive.

The model can be a vehicle for training or communicating with people relative to the way the system operates. Expected future performance patterns can be forecast. The model can be simulated before extensive data gathering to estimate the importance of different kinds of information. This later application can be particularly useful for forest modeling because the long forest life cycle delays the availability of some types of information.

The application of the System Dynamics Method to forest management systems (FMS) is difficult because the biological/human/financial interactions are so complex, reliable data is so limited, and the long forest life cycle is not synchronized with the much shorter political and organizational budget and administrative control cycles. Nevertheless it can be done by following the sequence described above.

Since the FMS is composed of many interrelated, but organizationally distinct, entities (e.g., the Congress; the Forest Service and other federal agencies; private forest owners; industrial forest owners; timber product producers; state and local governments; and private citizens and organizations which function as timber product users, forest facility users, environmentalists, voters, etc.) there is no single objective for forest management or concensus on priorities for the multiple uses in the short and long run. The resulting conflicts, compromises, and competition among the groups are important determinants of system performance and must be included in the hypothesis and model despite the difficulties in determining their nature. Biological data are limited in what has been measured and the length of the historical records. Government and private organization data is also limited in extend and duration. But enough is available to establish a general picture.

The dynamic hypothesis will have to capture the complex nature and couplings of the biological, human and financial feedback loops that comprise the FMS. The diagram in Figure 3 represents a beginning that will require elaboration through the collaboration of many people who are knowledgeable in the various areas. If the hypothesis development work is well done, equation writing (modeling) should not be too difficult. However, the large size and complexity of the FMS suggest that substantial time and effort will be required. The level of model detail required will be determined by the ways that the model will be used.

All model uses require two types of analysis -- validation and hypothesis testing. Validation is a procedure in which the performance and the structure of the model are compared empirically and theoretically to the real situation. The purpose is to determine whether the model is a sufficiently accurate representation of reality to be used in the ways required. Since the model omits the less important aspects of the system's structure, model performance is not expected to perfectly reproduce the known historical performance of the real system. But the major patterns must be regenerated "accurately enough." Statistical measures are used when possible to determine the degree of accuracy. Expert multidisciplinary judgment is used to evaluate adequacy.

Hypothesis testing involves a series of simulations designed to reveal any errors in the hypothesis relating to the creation of the performance patterns. Each simulation has a specific causal consequence to test and requires a prewritten statement of the performance expected to which the actual model performance is compared. All model uses require prior validation and hypothesis testing.

USES FOR SYSTEM DYNAMICS MODELS OF FOREST MANAGEMENT SYSTEMS

System Dynamics models are designed to serve the purposes for which they are constructed. The factors to be included, the level of aggregation, the types of evaluation variables, and the use of random variables (noise), exogenous variables, and data or analytic driving forces are all dictated by model purpose. There even may be several different models that are needed to answer different questions or generate different kinds of information. A models' validity can only be evaluated in the context of its purposes. Therefore, it is important to know the kinds of things SD models can do.

Loop Dominance Studies (Sensitivity)

SD models can be used to determine the relative contribution of different loops, policies, and/or parameters to the creation of important performance patterns. "Will Forest Service policies for permitted harvest volumes or budgets for forest maintenance and development have a greater influence on future standing timber volume growth?" is a sensitivity question that a SD model could answer. The influence of estimated parameters, such as average stand maturation time and designated habitat area required per wild turkey, on costs and growth rates also can be determined.

Data Value Studies

Policy, loop, and parameter sensitivity studies relate directly to the importance of measuring various relationships accurately. If a ± 20% change in a relationship has a small impact on model system performance, it is probably not necessary to spend a great deal to measure it to 5% accuracy. Most feedback systems are relatively insensitive even to fairly large changes (errors) in most parameters, but a few sensitive ones are usually present. It is extremely valuable to know which are critical and which are not.

Management Policy Laboratory

In most systems the management policies (the guidelines for how to make the required decisions) are not thoroughly understood. People have been using them for a while, perhaps many years, but they really do not understand their total impact on all aspects of system performance. The SD model can be used to test a policy's impact on any biological, organizational or financial variable in the model. The policy may be one currently in use, one proposed by the system managers or one arising from a creative synthesis by the SD analyst. Therefore, the model can be used as a management laboratory to answer "what would happen if ..." questions. This is an inexpensive way to identify ineffective or detrimental policies before they are tried in the real system where mistakes can be very expensive.

Forecasting of Future Performance Patterns

SD models can be used to forecast future time patterns. This is done in a simulation that starts the model accumulations at values corresponding to a real historical time, simulates the period of history up to the present and then continues the simulation into the (model) future. The patterns (trends and oscillations) created by the model are forecasts of the real system patterns. Future events usually cannot be accurately forecast in this way. An event is the value of a variable at a point in time. Therefore, a SD model could predict a growth trend in standing timber or an oscillation in budget, but the specific amount of standing timber at a particular time would not be as reliable as the pattern forecast.

Budget Request Justification

In a system with long response delays, such as a forest, a current decision can influence performance for many years. A SD model that considers biological, organizational and financial variables in the long run can be used to demonstrate the total long run impact of policies, particularly in budget areas. This could be of significant value for private timber companies or government agencies such as the Forest Service when considering budget formulation and when submitting budget requests for approval by boards of directors or The Congress.

Training

A SD model is a mathematical representation of a real system that has the same variables as the real system and operates the same way as does the real system. The model, unlike the real system, is accessible and manipulatable. Therefore, the model can be used to acquaint or train Forest Service staff, state forest managers, private forest owners, timber company managers, legislators, financial institution managers, environmentalists or the interested public. In particular, by changing model policies and parameters and observing the effects of these changes on behavior, people can be helped to better understand the dynamic forces at work in the real-world system. A SD model of a forest can be useful tool in public involvement as required by the NFMA and in conflict resolution since the resulting simulation is one of the most effective means available for supplementing and correcting human intuition. An interesting example of a SD training model is the "Criminal Justice System Training Model" developed by the author (4) for the Law Enforcement Assistance Administration.

Planning

Frequently, the people in an organization who first develop and use SD models are planners. Anyone who must estimate the long and short run consequences of many interrelated decision alternatives in a complex, imperfectly understood response environment and then must apply multiple, time dependent, politically sensitive evaluation criteria to the estimates has a very difficult task. The realism of System Dynamics models and their easy use through the DYNAMO Computer language can provide considerable help to forest system planners who face this type of situation daily.

CONCLUSION

Forest management systems are composed of many biological, human and financial accumulations and relationships that are organized into feedback loops that control the operation of the system parts and determine the performance patterns through time of the system variables. The System Dynamics Method has been developed to assist the understanding, modeling, planning, control, and improvement of systems of this kind. System Dynamics focuses more than other analysis methods on the whole system, information feedback control process that creates in a realistic way the dynamic performance patterns. Therefore, it seems appropriate to suggest System Dynamics' use as a tool to understand and improve forest management systems.

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Interrelationships Among the Biological, Financial and Silvicultural Decisions in Forestry

by

Willard R. Fey

and

Vernon L. Robinson

Presented at

National Silvicultural Workshop
May 19, 1983
Eugene, Oregon

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Interrelationships Among Biological, Financial, and Silvicultural Decisions in Forestry

by

Willard R. Fey and Vernon L. Robinson

Abstract

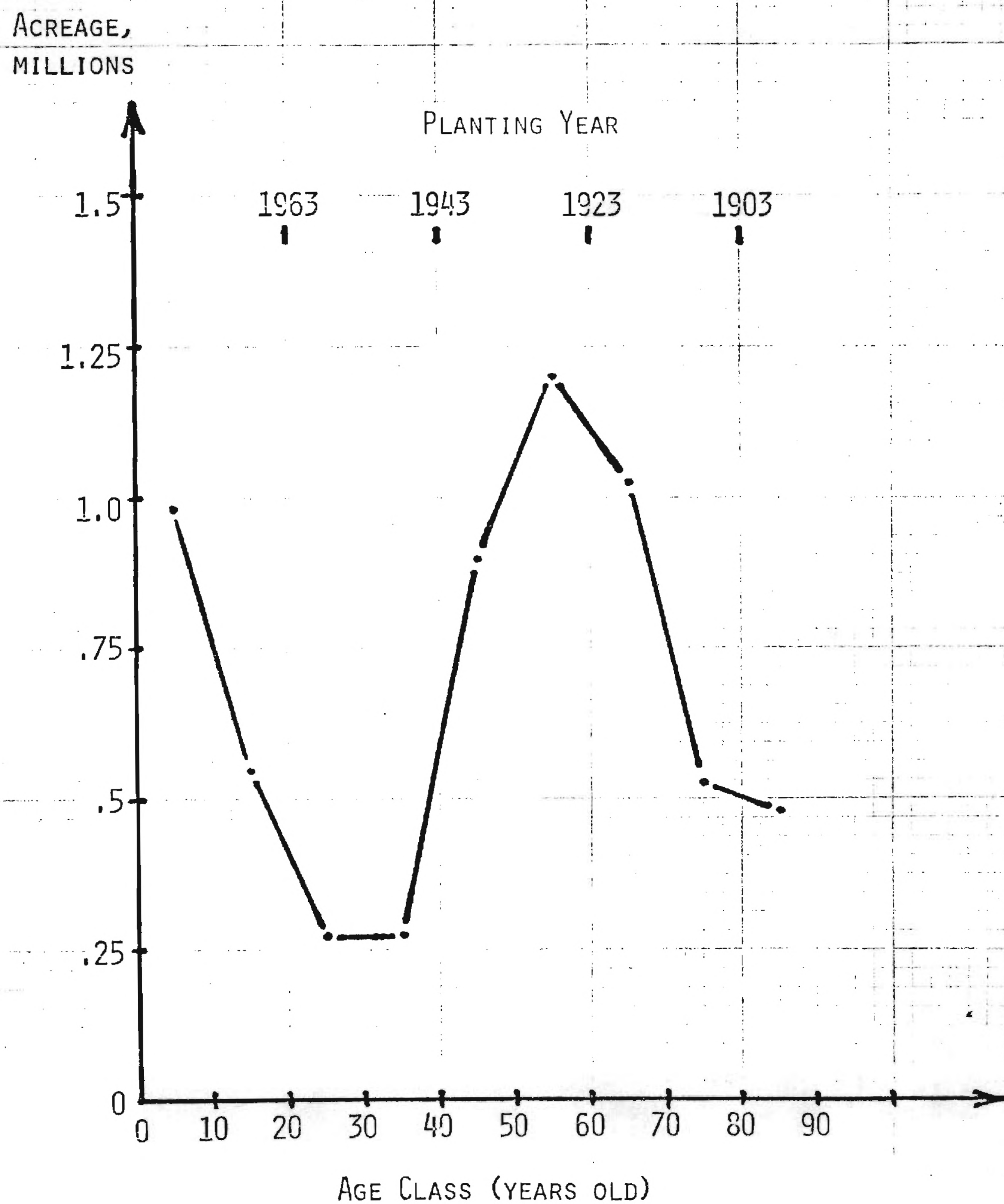
An important principle underlying the Forest Management and Planning Acts of 1974 and 1976 is that National Forests are ecosystems whose management requires consideration of the interrelationships among plants, animals, soil, water, air, and other factors. Such management is done in an administrative and financial environment that constrains and modifies actions to foster ecosystem balance. A system dynamics model of this complete forest management system for Region 8 has been developed to enable forest managers and planners to anticipate long run patterns of change in critical forest variables and to test the consequences of different decision policies relative to the biological, financial, and managerial aspects of the system in bringing about the desired ecosystem balance and benefits derived from the forest. Final model results are not yet available but examples of 200 year (1962-2162) simulated time histories of some critical forest variables are included to illustrate the way the model can be used.

Introduction

The Forest and Rangeland Renewable Resources Planning Act of 1974 (7) and the National Forest Management Act of 1976 (8) prescribe how land and resource management planning is to be conducted on National Forest System land. One of the guiding principles underlying these acts is the recognition that the National Forests are ecosystems whose management requires an awareness of the interrelationships among plants, animals, soil, water, air and other environmental factors within such ecosystems. Therefore, in the development and maintenance of land management plans, a systematic interdisciplinary approach is required to achieve integrated consideration of the physical, biological, economic, and other aspects of the National Forest System. Specifically, a team representing several disciplines is to be used at each level of planning to ensure coordinated planning which addresses outdoor recreation, range, timber, watershed, wildlife and fish, and wilderness opportunities.

The lack of information about the static relationships among these joint products of the forest makes the task of this team difficult. But the managerial job becomes much more difficult when one considers the dynamics of the situation facing the National Forest System in the South. Consider, for example, the acreage age class distribution in the Southern Region, Figure 1. For the next 30 years we see an increasing number of acres pushing into the older age classes followed by 30 years of a sharply declining number of acres. What kinds of problems will this distribution create for the timber sales and silviculturists of the Region? What will be the impact of these large acreage swings upon the joint products of the forest? In

FIGURE 1. REGION 8 SOFTWOOD ACREAGE BY 10 YEAR INTERVAL AGE CLASS.



light of the growing demand for all of these products, where and when is conflict likely to arise and what form is it likely to take? How do you manage the forest to reduce the potential for conflict among its various users? Are such timber harvest policies as regulation, even flow, 95 percent of CMAI, and average 18" DBH appropriate for both increasing and decreasing acerage flows or are more flexible policies required?

The answer to these questions cannot wait for the acreage swings to be upon us. Clearly, a model of the dynamic ecosystem coupled with the human intervention system is essential to meet the requirements of the above acts and to provide the analysis needed for formulating guidelines for the managerial decisions. The model described below is designed to demonstrate the utility of using a system dynamics approach to facilitate such an analysis.

Definition of System Dynamics

System Dynamics (SD) is a method of modeling the complex interactions that characterize our biological, engineering, managerial, organizational, and social systems. Its distinguishing feature is the application of feedback control principles to model problems. A feedback system exists whenever the environment leads to a decision that results in an action which affects the environment and thereby influences future decisions (2). Feedback control is fundamental to all life and human endeavor. For example, a thermostat receives temperature information and decides to start the furnace; this raises the temperature, and the furnace is shut off. A closing of the loop occurs, though a delay intervenes between the initial action and the feed back results. Closed loops and time delays are characteristic of all feedback processes.

The loops do not function separately, but rather are coupled together to form complex feedback systems that are whole interacting entities. Change in one system part eventually has an impact everywhere in the system. The continuing operation through time of these loops creates the performance time patterns of the system's variables. The study of feedback systems deals with the way information is used for the purpose of control. It helps us to understand how the amount of corrective action and the time delays in interconnected components can lead to system behavior. Thus system dynamics is based on the philosophy that the behavior of a system is principally caused by the system's structure. The structure includes not only the physical aspects of the system but, more importantly, the "policies" that dominate decision making within the system.

A second aspect of the SD philosophy is the concept that systems are viewed most effectively in terms of their underlying flows of people, money, materials, information, etc. A meaningful framework then results from tracing the cause-and-effect chains through the relevant flow paths of the system. A causal loop diagram is typically employed as the first step in modeling. These diagrams show the major cause-and-effect links between the system variables; indicating the direction of the linkage, and denoting the major feedback loops and their polarity. A positive feedback loop has very predictable behavior in response to a change induced in any of its variables. The loop can only act to reinforce or accelerate that initial change. A negative feedback loop on the other hand acts to counter the direction of initial change in any of its variables. This frequently leads to oscillation.

From this perspective, all dynamic systems can be represented in terms of level and rate variables with auxiliary variables used to represent goals and other concepts that affect the rates. A level is an accumulation or an integration over time of flows or changes that come into and out of the level. For example, forest inventories grow or diminish over time depending upon the relative growth and harvest of the forest. A rate variable on the other hand is a flow or a decision that controls a flow into or from an accumulation. Forest system relationships can be translated into level, rate, and auxiliary equations that can be simulated by computer using a specially designed compiler program called DYNAMO (6).

Ecological Systems as Feedback Processes

Ecology is the study of organisms in relation to their environment (5). A community is an aggregation of living organisms having mutual relationships among themselves and their environment. Forest ecology, therefore, is concerned with the forest as a biological community with the interrelationships between the various trees and other organisms comprising the community and between these organisms and the physical environment in which they exist. The forest community and its habitat together comprise an ecological system, or ecosystem, in which the constituent organisms and their environments interact in a complex energy cycle.

This cycling of mineral nutrients from the soil to the vegetation and back again is basic to all life. Therefore, it provides a useful starting point for modeling the interrelationships that exist in a forest ecosystem. In such a system energy, primary production, biomass, dead organic matter, and inorganic nutrients are accumulated. These accumulations are determined by the material flows around the energy cycle and by the time delays that exist between these fundamental ecological variables. The coupling of positive and negative feedback loops in the forest ecosystem will produce a time history of forest biomass accumulation which we commonly refer to as a yield table.

In order to construct a testable model (3), this process must be articulated in terms of quantifiable interloop and intraloop relationships representing other variables of interest that exist within the forest ecosystem. The purpose here is merely to demonstrate that the balance of nature means that ecological systems are feedback processes. Hence, system dynamics is an appropriate tool for studying the complex interrelationships that exist among the trees and other variables.

Silvicultural Intervention in Forest Ecosystems

Silviculture is the theory and practice of controlling forest estalishment, composition, and growth in order to make the forest permanently useful to mankind (4). Traditionally the activities of the silviculturist focused upon producing greater economic timber values. But it is now becoming increasingly clear that these same activities shape the composition of the forest and hence the proportion and distribution of the land into different timber types and age classes from which all benefits of the forest are derived (1). For example, a stand of old-growth timber offers den trees for bear and mast for squirrels, but little browse for deer; undisturbed, the old growth stand minimizes sediment flow into streams but also minimizes the annual runoff of water. Large trees are aesthetically pleasing to recreationists and large logs, when harvested, provide premium quality solid wood products. A young forest, on the other hand, provides a different array of benefits.

The important point is that silvicultural intervention in the forest ecosystem has an impact upon the benefits received and, therefore, must be modeled to capture the reality within the forest ecosystem. There are several characteristics of this relationship that are important. First, a balance is required between forest development and use. Too much use destroys the forests' ability to reproduce itself. Too little use provides inadequate benefits to the users. "Appropriate" use simultaneously provides significant benefits while enhancing forest productivity and vigor.

The second consideration is the synergy or conflict among the users. Usually a utilization action such as cutting an area for timber has benefits and detriments relative to other uses. For example after cutting, an area frequently becomes available for grazing for a period of time after new trees are established and until they are large and dense enough to interfere with grazing. Temporary detriments arise as certain creatures' habitats are destroyed along with some of the scenic beauty of the area. These tradeoffs become important considerations in forest management decisions.

A third consideration is the response time horizon. An action may be beneficial in the short run for some purpose, but detrimental in the long run for that same purpose or others and vice versa. Mining an area may provide significant immediate revenues, but may contaminate the land in such a way that reforestation cannot take place for many years. Burning may destroy biomass in the short run, but increase plant productivity and habitats of desirable creatures in the long run.

The interventions by silviculturists usually require continuing actions, observation, and evaluation to ensure that the desired results occur and persist. This requires a continuing organization and management with authority and responsibility to determine and carry out the required tasks. The Forest Service is an obvious example of a continuing organization engaged in forest management necessitated by the need to continuously balance development and use, control coordination and tradeoffs between uses, and reasonably balance short and long range benefits and detriments.

Financial considerations and constraints arise as soon as a continuing management activity is supported. Furthermore, the balancing of forest development and use, the control of multiple uses, and the balance of short and long range considerations all contribute to the continuing need to provide costly intervention activities before benefits are realized. If money is required, a source must be found and control must be exercised over the utilization of funds. The consequence of this reality is that the forest biology, the decision structures of the associated human organizations, and the financial aspects of forest benefits, capital and operating costs of the organizations all become interrelated in the short and long run to form a single entity--the forest management system. The biological, human, and financial aspects of this system are related through coupled feedback loops that operate continuously through time to create the patterns (growth and oscillation) of the system's variables.

These are the consideratios which form the basic structure of the demonstration model described below. The key features of the model are the feedback processes, with multiple coupled loops and time delays, and the interdependence of the biological processes, managerial decision making, and financial considerations that constitute the forest management system.

System Dynamics Model of the Forest Management System of Region 8

The System Dynamics Model of the Region 8 Forest Management System (R8FMS) includes a set of equations which represents the causal relationships between the biological, managerial and financial activities that operate through time to create the system's historical patterns of performance. The current equations are the authors' best estimate of the policies and parameters of the system. However, extensive validation studies have not yet been done, so suggestions for improvement are welcome. The purpose of this paper is to illustrate how feedback principles apply to this system and to show how such a model, when properly validated, could be used to contribute to the planning, forecasting, and decision making activities at the congressional level and the national, regional, and individual forest levels in the Forest Service.

The R8FMS model is divided into seven sectors. These are timber, wildlife, recreation, budget, staff, forest products industry, and government and economy condition. Several important areas have been omitted for simplicity. These include range, soil, water and fish. Areas devoted to wilderness and mineral development are included in the timber sector. As the model is improved, existing sectors will be extended and refined and omitted areas will be added. The forest products industry and government/economy condition sectors represent exogenous influences from these areas in the form of projected time histories. These also need refinement.

The model is simulated over a 200 year period from 1962 to 2162. Each of the 182 dynamic variables is calculated annually. Time graphs of 46 of these variables are plotted. The first 20 years (1962-81) reconstruct actual history for which some data exist. Four variables' data are plotted--budgets for timber, wildlife and recreation and timber sales. 1962 was selected as the starting year because the data could not be found or estimated for some variables before that time. Long run Forest Service goals (1983-2029) are plotted for timber sales, wildlife improvement acres and recreation visitor days.

The important flows and feedback relationships included in the model are shown in Figures 2-8. The fundamental timberland loop is a positive one (Fig. 2) in which old stand timber "Acres Ready to Harvest" are perceived as a revenue opportunity that leads to "Land Clearing Harvest". That harvest reduces the "Acres Ready to Harvest" and increases the "Cleared Acres". After a short delay (2-3 years) the cleared acres are regenerated (trees are

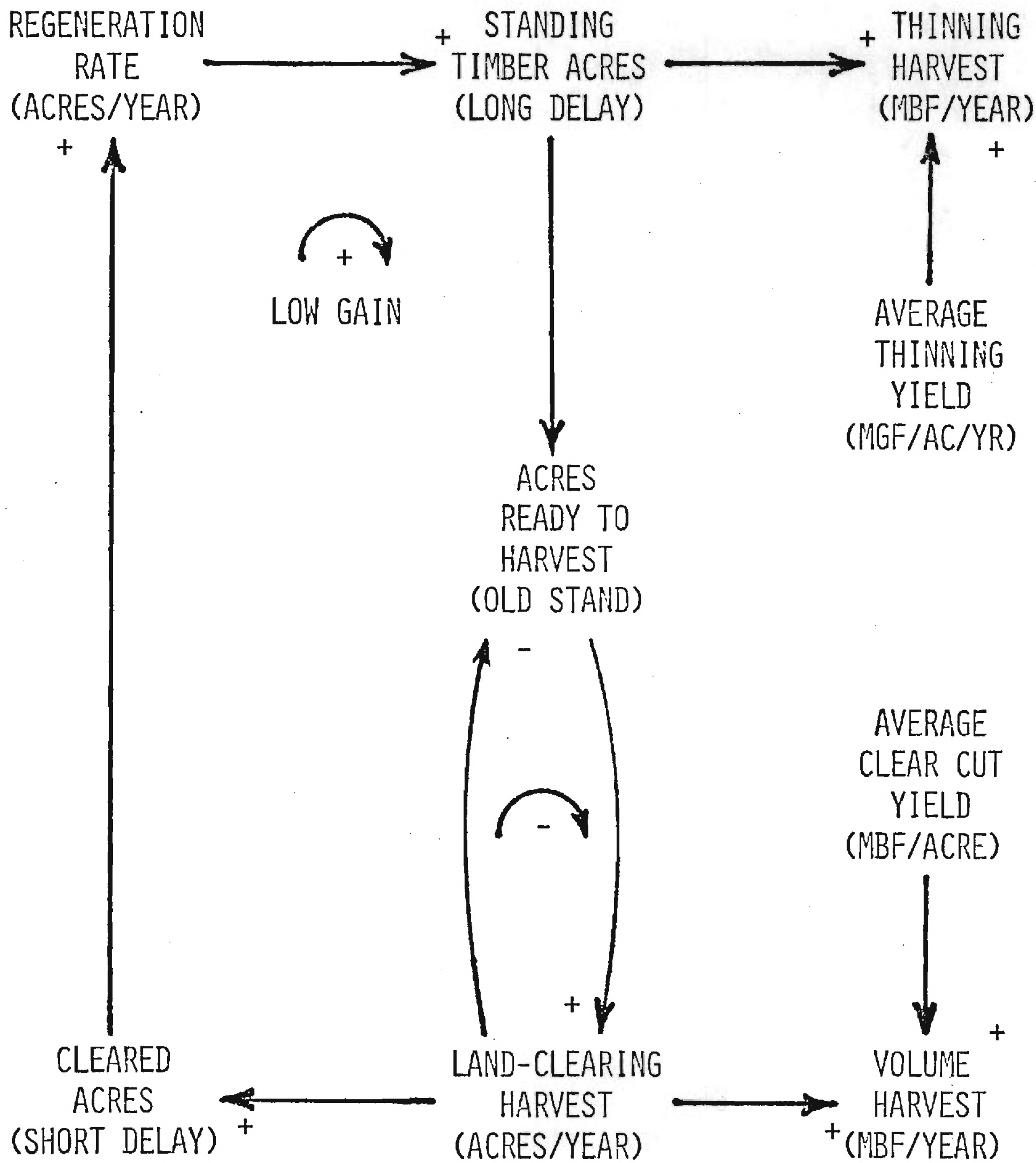


FIGURE 2. FUNDAMENTAL TIMBERLAND FEEDBACK LOOP WITH SAW TIMBER AND PULPWOOD HARVEST GOAL.

replanted) either through natural seeding or planting by the Forest Service (FS). After a long growing delay (60-150 years depending on the type of trees involved) the acres again become ready to harvest. This is a positive loop with low gain, so sustained growth in acres per year harvested is not possible unless new land is added. Timber harvest in thousand board feet (MBF) is determined from acres harvested and yield per acre for cleared land and from the volume of commmercial thinning.

The arrow from "Acres Ready" to "L-C Harvest" in Fig. 2 represents the harvest decision. Many things influence that relationship. Figure 3 and Figure 4 are needed to show the factors included in the model. Pressures from recreation, wildlife and timber management considerations are shown in Fig. 3. Financial and staff pressures appear in Fig. 4.

Planning for the harvest is done about 5+ years before the actual harvest. There are 3 years before Congress acts on the plan and two to three more years after the sale of the timber before cutting is done. The plan includes "Acres Ready to Harvest" modified by "Wildlife Pressures" (do not cut too much old growth, so sufficient old stand habitats are retained; but cut enough to provide sufficient early growth habitats) and "Recreation Pressures" (do not cut so much old growth that visual beauty is destroyed, but cut enough so that early and middle growth hunting is assured and a fairly open, parklike vista is created). "Expected Forest Products Industry Demand" is also important. This is based on past demand. The "Planned Harvest" after a three year delay is considered by Congress in determining "Timber Budget". "Political Pressures" and other factors also influence "Timber Budget." The timber "Sales Goal" follows with some variability from the "Planned Harvest" and "Timber Budget". The "Sales Goal" becomes actual sales and, then two to three years later, "Land Clearing Harvest" unless "FP Industry Demand" is insufficient.

The varying recreation, wildlife and timber pressures to harvest do not in general lead to a constant year-to-year harvest in area or MBF. The model provides the option to select a harvest decision that maintains an area/rotation policy which will achieve a balanced distribution of acres in different age classes and attain the long-term sustained-yield capacity of the forest (i.e., a regulated forest).

There are also budget and staff influences on the harvest decision (Fig. 4). The harvest should be large enough to provide work for the existing permanent ranger staff, but not so large as to require hiring large numbers of new people. The existing staff is a reflection of past harvest volumes. The "Planned Budgets" must provide for the "Planned Harvest" without increasing substantially beyond the previous year's budget. The "Planned Budget" is then considered with "Planned Harvest" by Congress in setting "Timber Budget."

There are three places in the model where timber, wildlife and recreation considerations interact. The first is the harvest decison. Total harvest depends on all three pressures. The second is budget. If all of the individual budget requests cannot be met, the budget allocation to each area will be dependent on the area's own needs, the needs in the other areas and the priorities assigned to each.

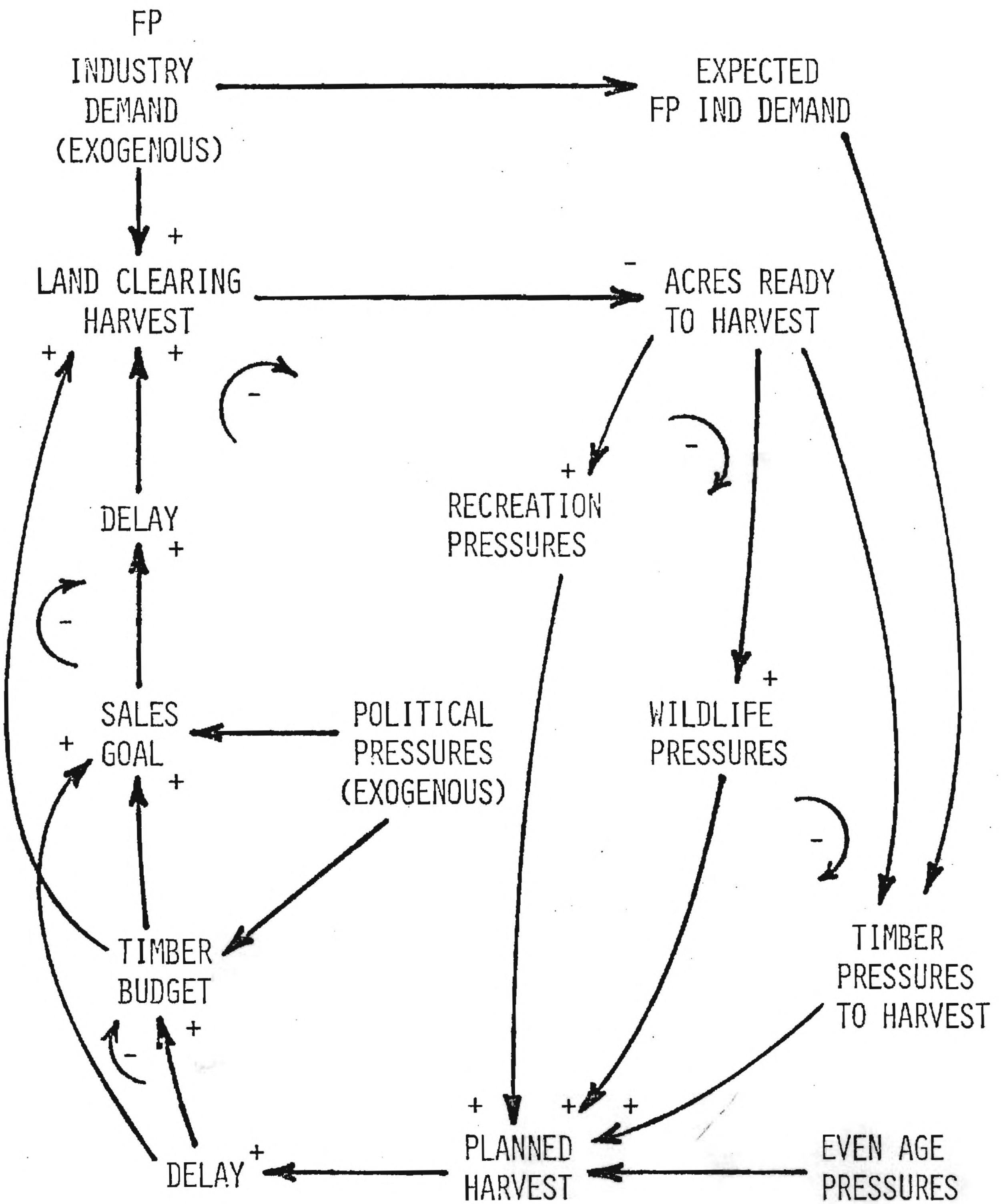


FIGURE 3. TIMBER HARVEST LOOPS FROM TIMBER, RECREATION AND WILDLIFE MANAGEMENT PRESSURES.

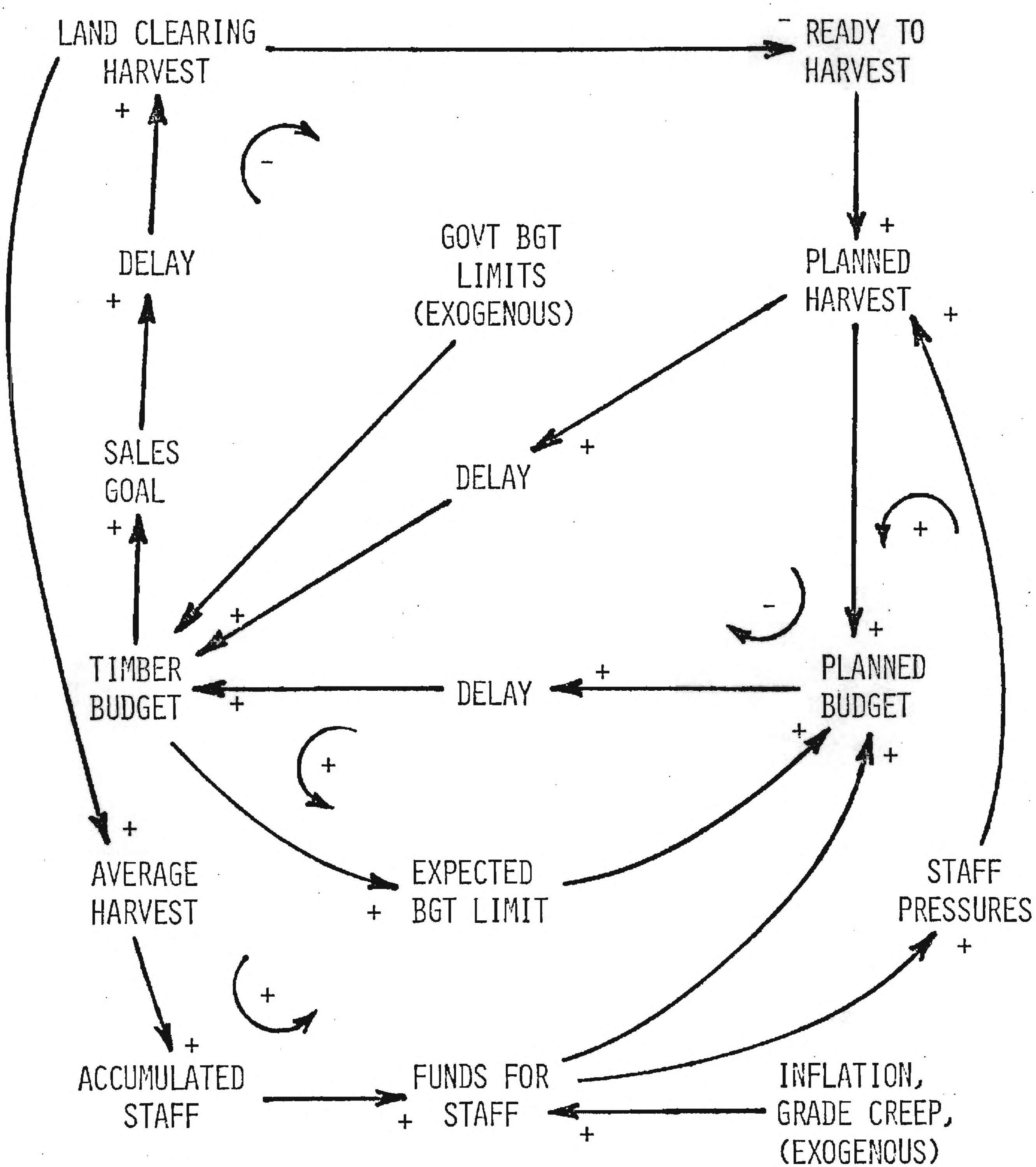


FIGURE 4. TIMBER HARVEST LOOPS FROM STAFF, FINANCIAL AND INFLATION PRESSURES.

The third interaction occurs in regeneration. Once the land is harvested it must be regenerated either naturally or artificially. The regeneration decison (Fig. 5) could be affected by considerations for timber, wildlife and recreation. In the model regeneration is further complicated by the three types of forest that are included. These are softwood natural stand, softwood plantation with improved trees and hardwood. Regeneration is based on acreage ready for regeneration and three primary proportions--the fraction of old softwood land to be regenerated as softwood plantation area; the fraction of old hardwood land to be regenerated as softwood plantation land; and the fraction of softwood land to be regenerated as hardwood land.

In recent years the trend has been toward softwood land because softwoods grow faster and there is greater demand for softwood timber. However, natural forest biology is biased toward hardwood forest, the successional climax condition. There is then a natural tendency for softwood land to become hardwood bearing, so it requires money and effort to keep the latter fraction small. The natural stand vs. plantation fraction balances long run greater plantation yield with short run greater plantation cost. The desired softwood vs hardwood proportion is dependent on expected timber demand for the two types, wildlife considerations (hardwoods are needed for most species for mast and dens) and recreation needs hardwoods are more attractive areas especially in the fall. Water, soil and range considerations are omitted for simplicity. The plantation vs. natural stand regeneration influences are shown in Figure 6.

The natural stand, plantation and hardwood stands are each divided into five age classes: seedling, sapling, pole, small saw timber and large saw timber areas (Fig. 7). Cleared land, wilderness area, and land devoted to mineral development are also included as shown by these flows and accumulations.

The generation of budgets and performance goals for timber, wildlife and recreation is shown in Figure 8. Planned performance leads to planned budget needed to carry out the performance with constraints imposed if total planned budget is greater than the government's budget limit. The final budget sets the performance goal which determines the actual performance. Past performance then influences planned future performance. When the total budget for timber, recreation and wildlife exceeds the maximum budget set by Congress, all three budgets must be reduced. The model reduces them proportionately, but priority weighting could be used.

Model Uses in Forest Management Planning and Decision Making

System Dynamics models are designed to serve the purposes for which they are constructed. The factors to be included, the level of aggregation, the types of evaluation variables, and the use of random variables (noise), exogenous variables, and data or analytic driving forces are all dictated by model purpose. There even may be several different models that are needed to answer different questions or generate different kinds of information. A model's validity can only be evaluated in the context of its purposes. Therefore, it is important to know the kinds of things SD models can do.

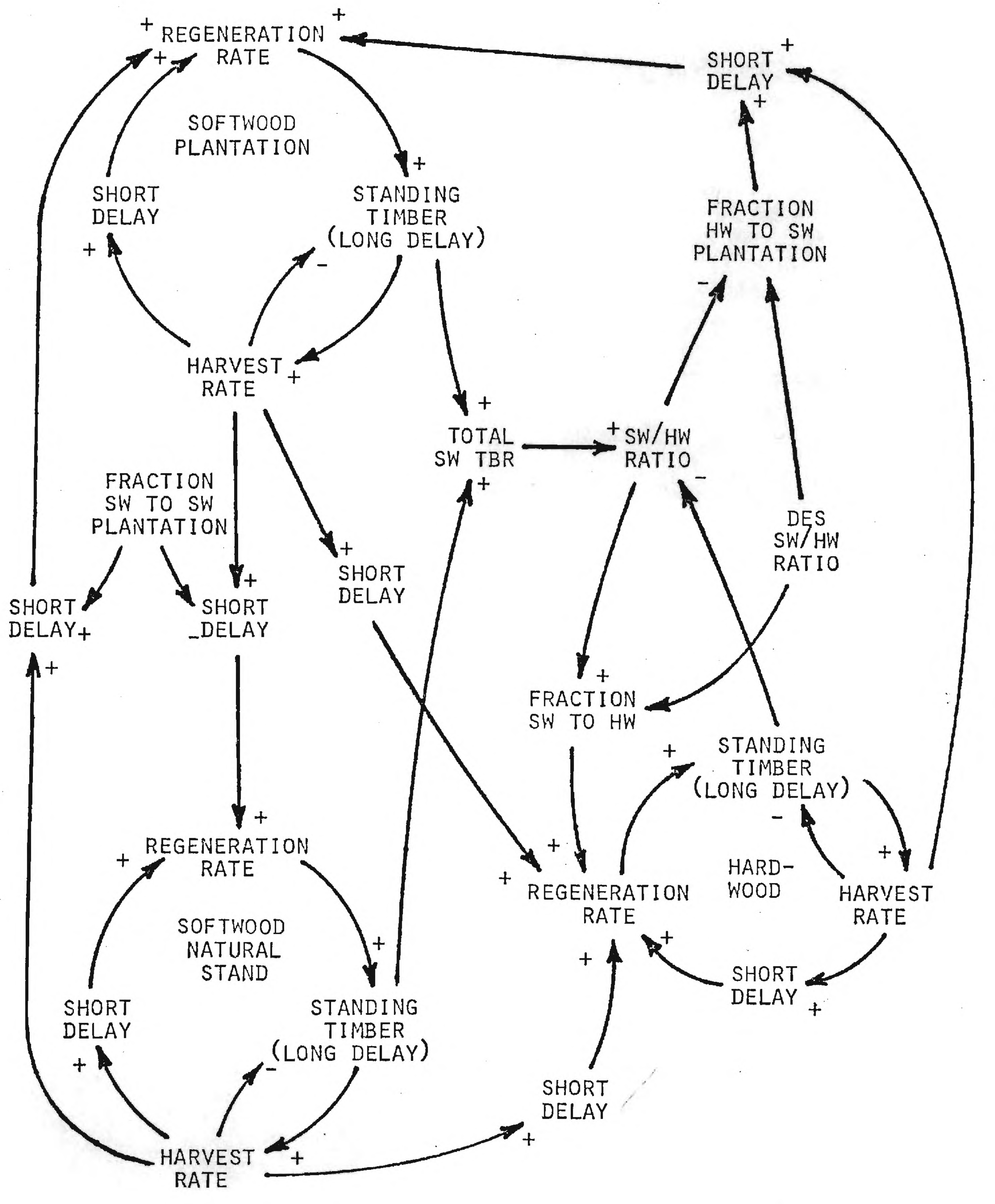


FIGURE 5. INTERACTIVE SUCCESSION CYCLE FOR HARDWOOD, SOFTWOOD PLANTATION AND NATURAL STAND FOREST TYPES.

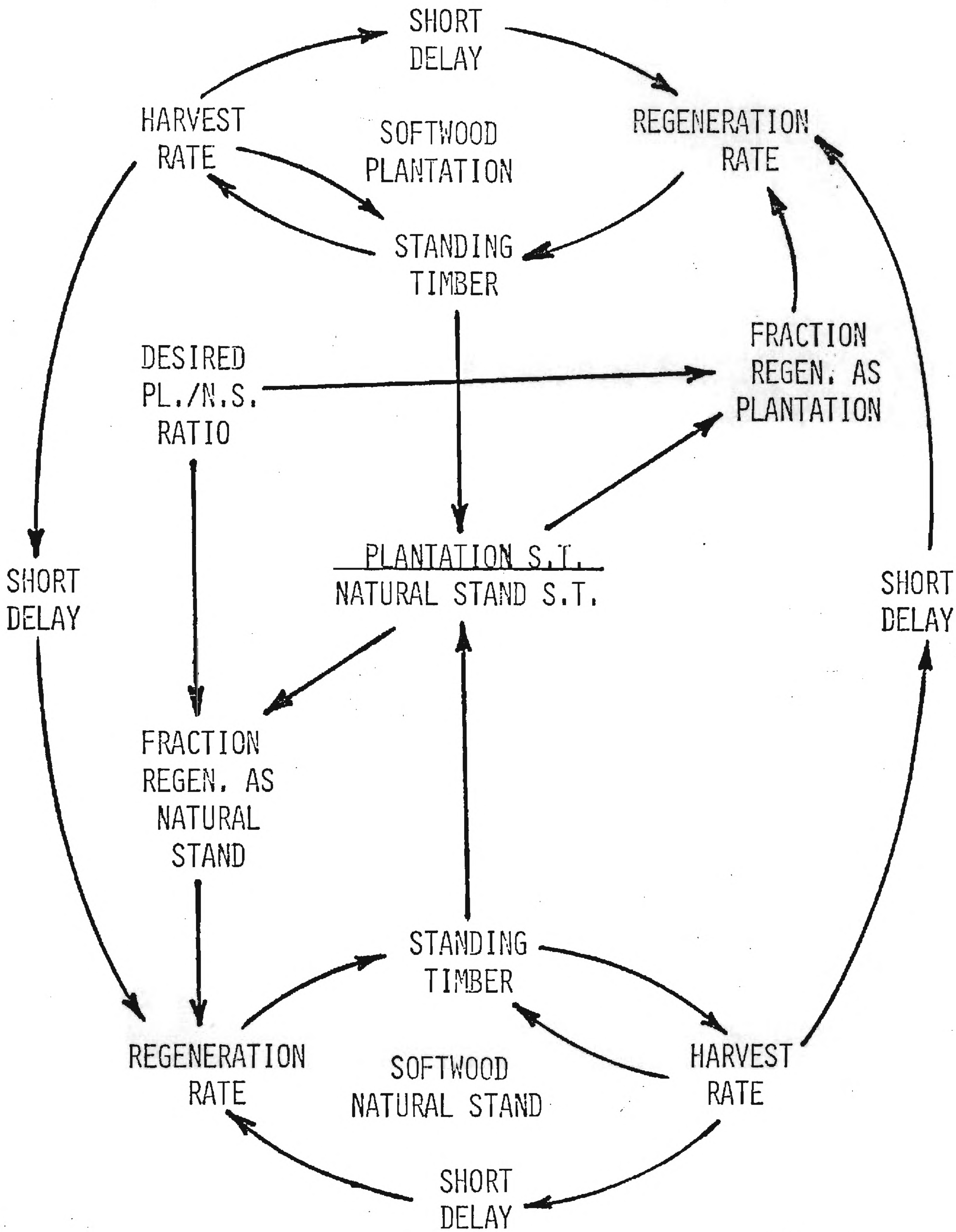


FIGURE 6. TRANSITION CONTROLS FOR A SOFTWOOD NATURAL STAND VS. PLANTATION BALANCE.

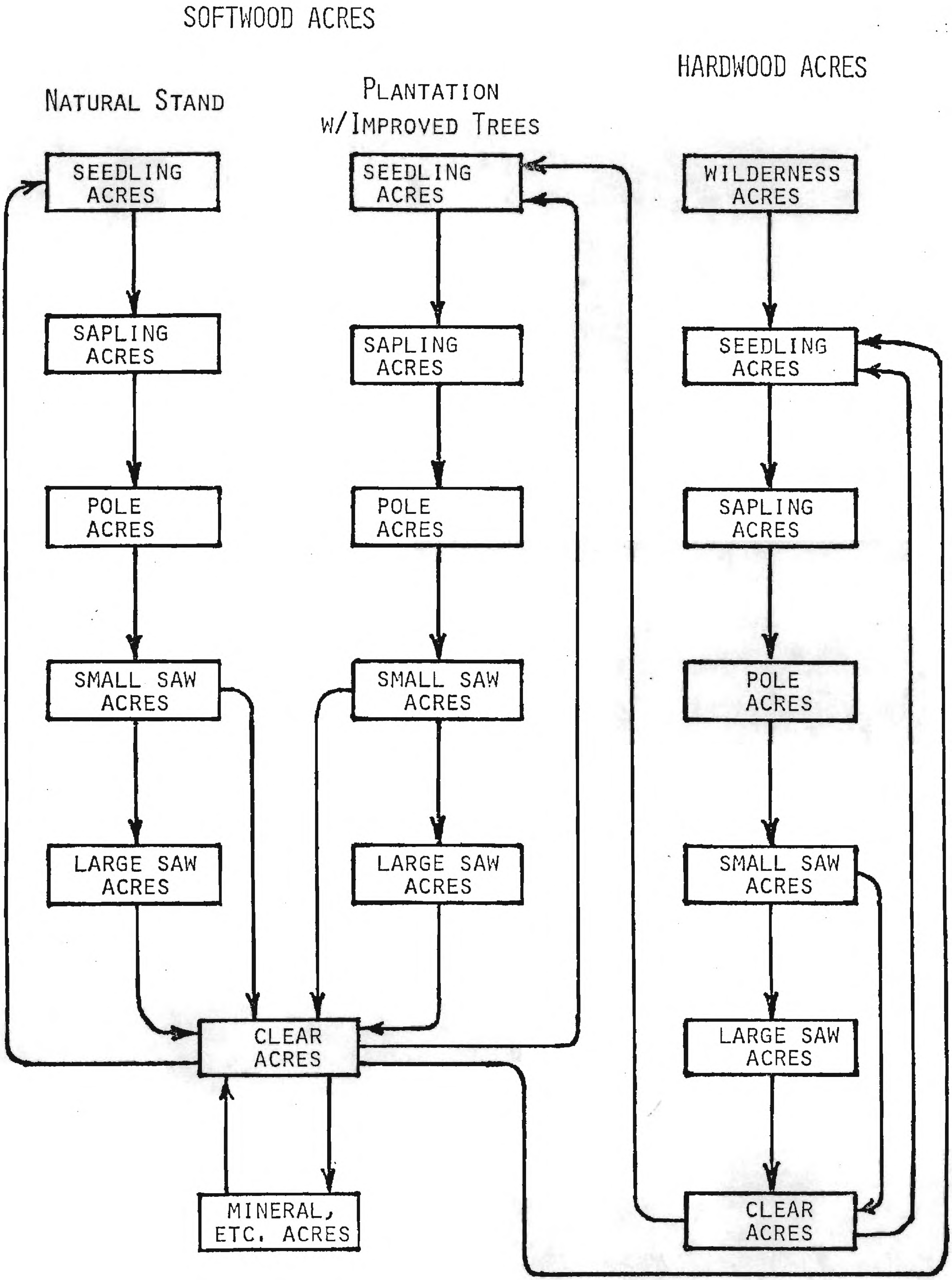


FIGURE 7. TIMBER LAND AGE CLASSES AND FLOWS FOR HARDWOOD, SOFTWOOD PLANTATION AND NATURAL STAND AREAS.

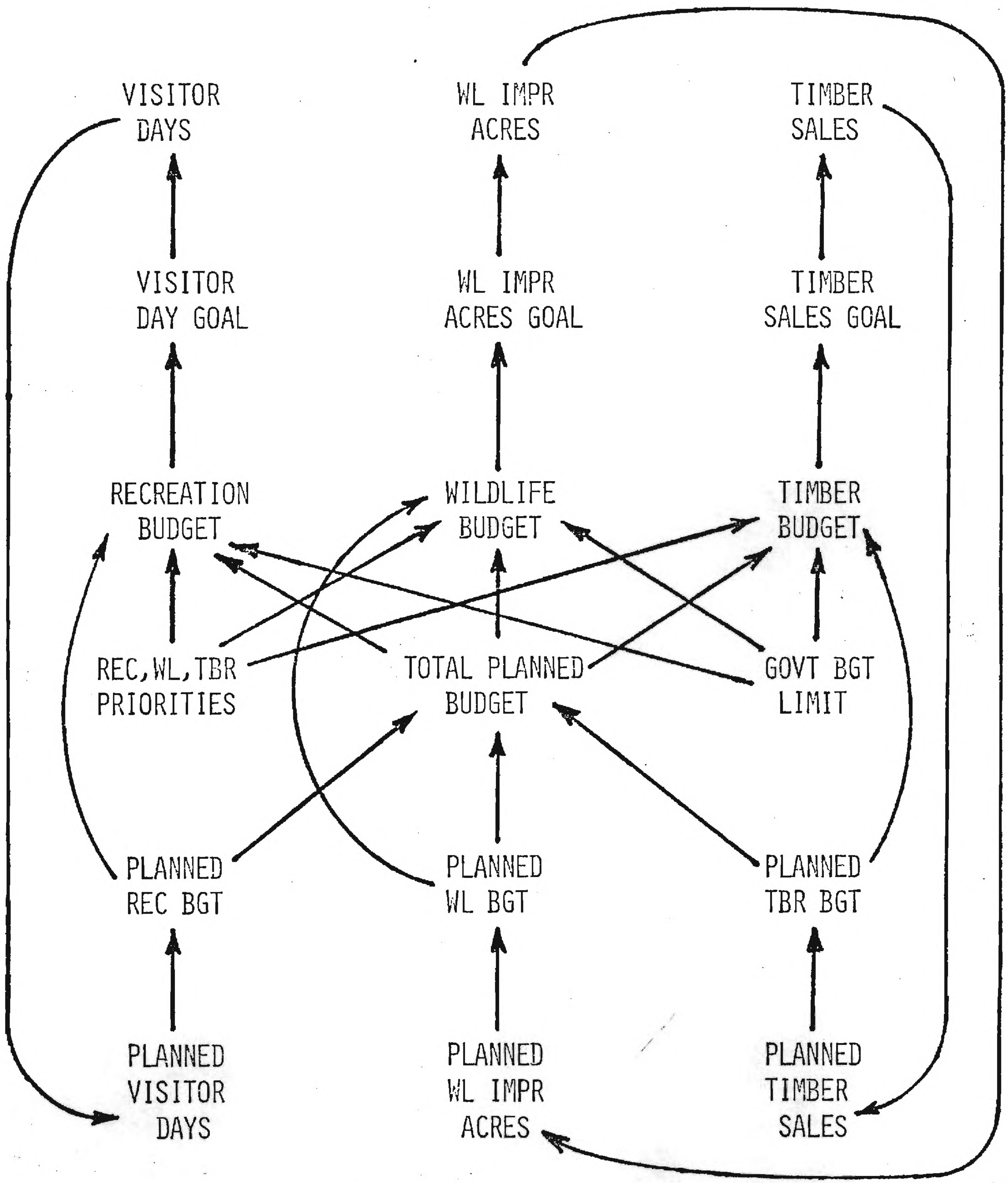


FIGURE 8. INTERACTIONS BETWEEN PLANS, GOALS AND OUTCOMES FOR BUDGETS AND ACTIVITIES IN RECREATION, WILDLIFE AND TIMBER MANAGEMENT

The timber sales decision with its supporting (or controlling) budget and demand constraint dominates the long run dynamic performance of the forest system. The regeneration decision which determines the proportions of the cleared land that are to be recycled with hardwood, natural softwood and improved softwood stands is an important secondary influence. Different policies for making these decisions can lead to very different patterns of availability of forest resources and of benefits realized.

The model is used to clarify the causes of the performance patterns, determine the importance of accurate data and test the dynamic consequences of different decision policies by calculating model performance annually over a long period of time. The model is still in development, so successful simulations are not yet available. However, an hypothetical model simulation is shown in Figure 9. Four variables (annual timber sales, wildlife improvement acres, recreation visitor days and total system budget) are included to illustrate the appearance of a simulated 200-year time plot. The patterns of the variables and the relationships between them for the decision policies used can be seen at a glance.

When the model is operating properly many simulations will be run each with one or more differences from all other runs in parameter values, exogenous variables' time histories or 1962 starting conditions. Differences in simulated performance patterns can then be attributed to the factor differences. Figure 10 shows an hypothetical plot of timber sales for three different decision policies--normal, regulated forest and severe budget constraint. A manager or planner could draw important conclusions about the desirability of following different policies by examining the results of a plot like the one in Figure 10. Several model uses are discussed in the following sections.

Loop Dominance Studies (Sensitivity)

SD models can be used to determine the relative contribution of different loops, policies, and/or parameters to the creation of important performance patterns. "Will Forest Service policies for permitted harvest volumes or budgets for forest maintenance and development have a greater influence on future standing timber and growth?" is a sensitivy question that a SD model could answer. The influence of estimated parameters, such as average stand maturation time and designated habitat area required per wild turkey, on costs and growth rates also can be determined.

Data Value Studies

Policy, loop, and parameter sensitivy studies relate directly to the importance of measuring various relationships accurately. If a ± 20% change in a relationship has a small impact on model system performance, it is probably not necessary to spend a great deal to measure it to 5% accuracy. Most feedback systems are relatively insensitive even to fairly large changes (errors) in most parameters, but a few sensitive ones are usually present. It is extremely valuable to know which are critical and which are not, so data gathering resources can be concentrated on sensitive areas.

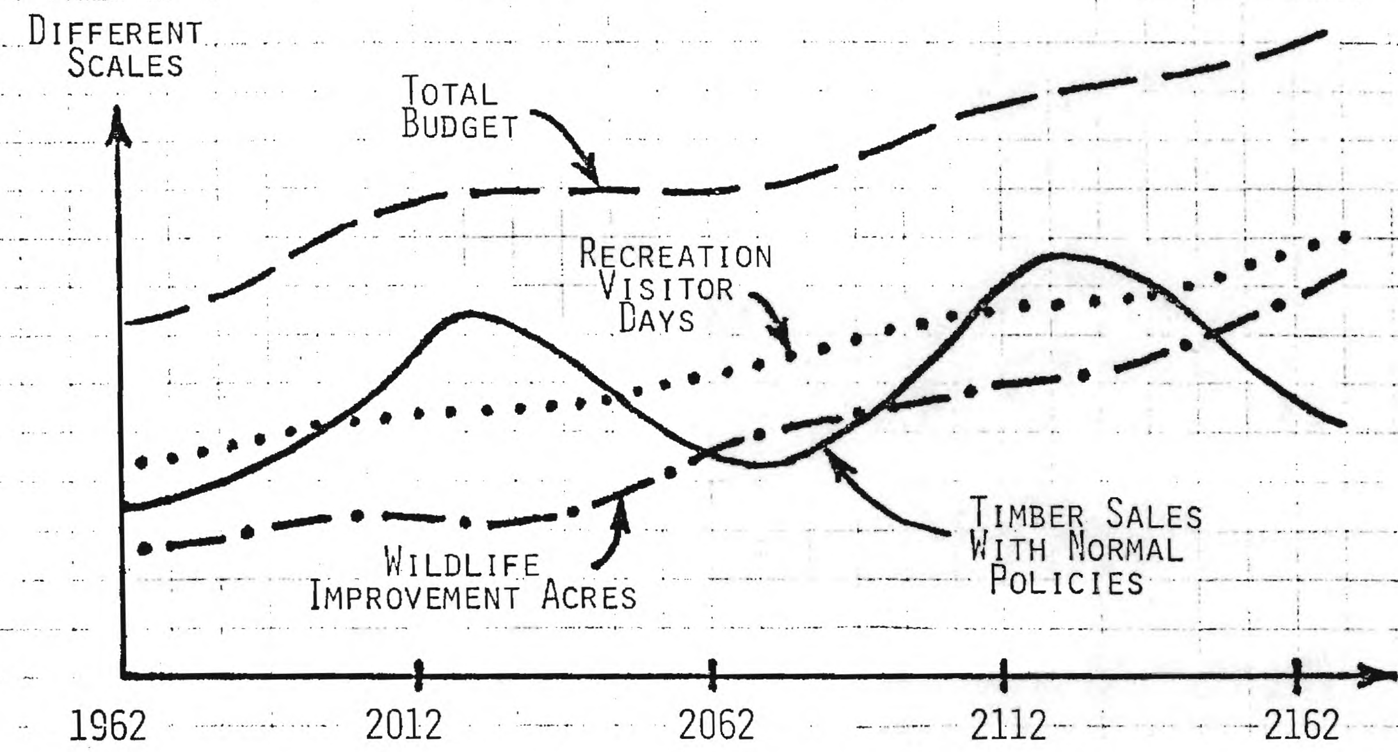


FIGURE 9. HYPOTHETICAL 200 YEAR MODEL SIMULATION SHOWING BUDGET, TIMBER SALES, WILDLIFE IMPR ACRES AND VISITOR DAYS.

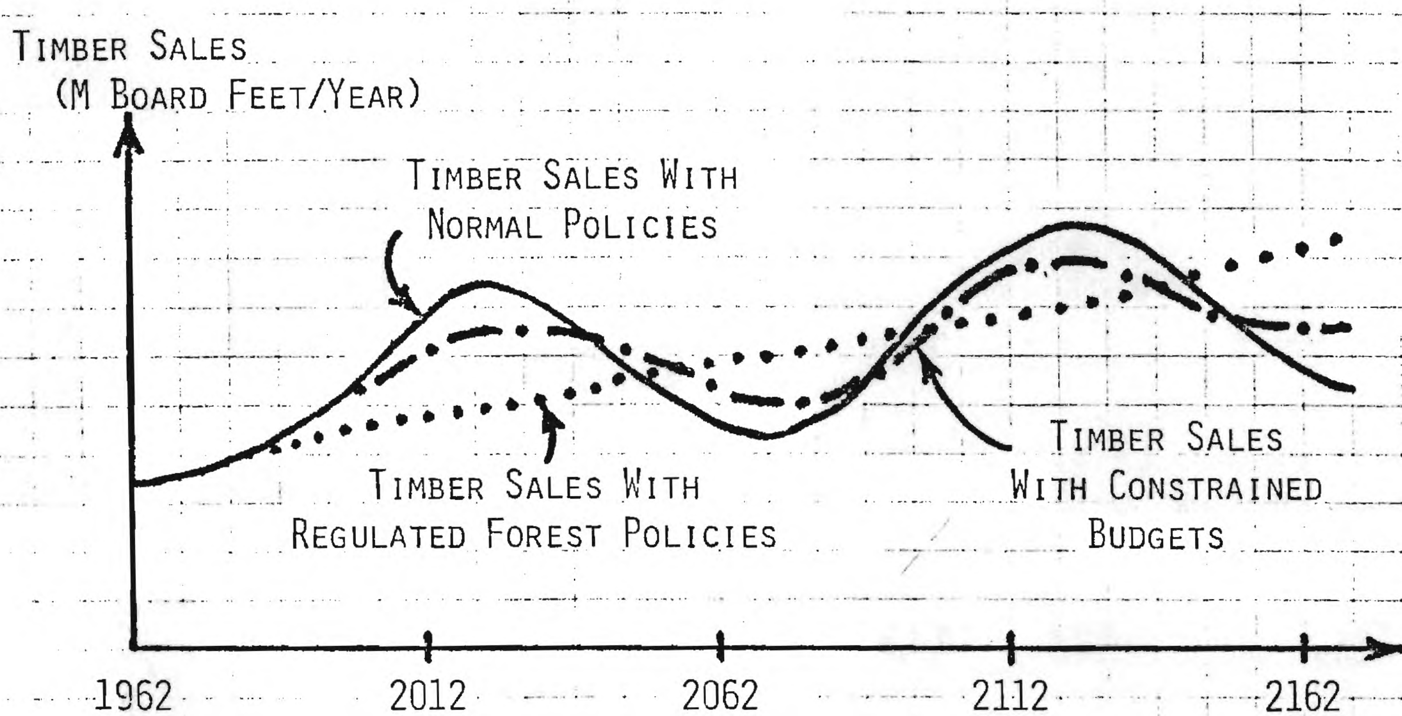


FIGURE 10. TIMBER SALES FROM THREE DIFFERENT HYPOTHETICAL SIMULATIONS SUPERIMPOSED FOR EASY COMPARISON.

Management Policy Laboratory

In most systems the management policies (the guidelines for how to make the required decisions) are not thoroughly understood. People have been using them for a while, perhaps many years, but they really do not understand their total impact on all aspects of system performance. The SD model can be used to test a policy's impact on any biological, organizational or financial variable in the model. The policy may be one currently in use, one proposed by the system managers or one arising from a creative synthesis by the SD analyst. Therefore, the model can be used as a management laboratory to answer "what would happen if ..." questions. This is an inexpensive way to identify ineffective or detrimental policies before they are tried in the real system where mistakes can be very expensive.

Forecasting of Future Performance Patterns

SD models can be used to forecast future time patterns. This is done in a simulation that starts the model accumulations at values corresponding to a real historical time, simulates the period of history up to the present and then continues the simulation into the (model) future. The patterns (trends and oscillations) created by the model are forecasts of the real system patterns. Future events usually can not be accurately forecast in this way. An event is the value of a variable at a point in time. Therefore, a SD model could predict a growth trend in standing timber or an oscillation in budget, but the specific amount of standing timber at a particular time could not be forecast as reliably as the pattern.

Budget Request Justification

In a system with long response delays, such as a forest, a current decision can influence performance for many years. A SD model that considers biological, organizational and financial variables in the long run can be used to demonstrate the total long run impact of policies, particularly in budget areas. This could be of significant value for private timber companies or government agencies such as the Forest Service when considering budget formulation and when submitting budget requests for approval by boards of directors or Congress.

Training

A SD model is a mathematical representation of a real system that has the same variables as the real system and operates the same way as does the real system. The model, unlike the real system, is accessible and manipulatable. Therefore, the model can be used to acquaint or train Forest Service staff, state forest managers, private forest owners, timber company managers, legislators, financial institution managers, environmentalists or the interested public. In particular, by changing model policies and parameters and observing the effects of these changes on behavior, people can be helped to better understand the dynamic forces at work in the real-world system. A SD model of a forest can be a useful tool in public involvement as required by the NFMA and in conflict resolution since the resulting simulation is one of the most effective means available for supplementing and correcting human intuition.

Planning

Frequently, the people in an organization who first develop and use SD models are planners. Anyone who must estimate the long and short run consequences of many interrelated decision alternatives in a complex, imperfectly understood response environment and then must apply multiple, time dependent, politically sensitive evaluation criteria to the estimates has a very difficult task. The realism of System Dynamics models and their easy use through the DYNAMO computer language can provide considerable help to forest system planners who face this type of situation daily.

Conclusion

Forest management systems including Region 8 are composed of many biological, human and financial accumulations and relationships that are organized into feedback loops that control the operation of the system parts and determine the performance patterns through time of the system variables. The system dynamics method has been developed to assist the understanding, modeling, planning, control, and improvement of systems of this kind. system dynamics focuses more than other analysis methods on the whole system, information feedback control process that creates in a realistic way the dynamic performance patterns far into the future. Therefore, it seems appropriate to suggest system dynamics' use as a tool to understand and improve forest management systems.

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